Seasonal migratory behavior of *Mythimna separata* (Lepidoptera: Noctuidae) in Northeast China

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Abstract: *Mythimna separata* (Walker) is a vital pest insect in China. In order to identify the parameters of seasonal migratory behavior of *M. separata* (Walker) in Northeast China, long-term observation was carried out by vertical-looking radar (VLR) and light traps in Jilin province in 2005, in combination with analysis of large-scale wind systems and trajectory simulation based on GIS. The results showed that migration of *M. separata* moths only occurred on a few nights during each of three distinct migration periods; they flew at obviously different altitudes depending on season and time of night, and their migratory behavior was significantly influenced by meteorological conditions, especially the large-scale atmospheric circulation. The long-distance migration was windborne, and flights of *M. separata* moths could be observed throughout the night. The flying altitude in spring was mainly 300 – 600 m, while that in autumn was relatively low, mainly below 500 m. Radar echoes in summer were obvious in layers, indicating that the migrants were sometimes concentrated into two or more layers, mainly in 500 and 700 m, with a maximum height of up to 1 000 m. Trajectory analysis showed that on May 29 and June 1, *M. separata* populations flying over the radar station originated from the southwest, probably from Shandong province. In mid-July, however, these populations were locally landed and showed relatively short-distance dispersal under the influence of convective weather. On September 11, *M. separata* populations originating from the Hulun Buir region of Inner Mongolia were observed to fly on northwesterly winds to the southeast of Jilin province. The results provided technical support for the effective prevention and control of armyworm in Northeast of China.

Key words: *Mythimna separata*; migration; radar observation; trajectory analysis; vertical-looking radar (VLR); light trap; population source

1 INTRODUCTION

Mythimna (= *Pseudaletia*, *Leucania*) *separata* (Walker) (Lepidoptera: Noctuidae) is a worldwide pest (Chen and Bao, 1987); it is widely distributed throughout China except in the far northwest (Xinjiang). The larvae are known as 'armyworms' and can damage more than 104 species of plants in 16 families including cereal food crops (wheat, rice, foxtail millet and corn), industrial crops (cotton and beans), and vegetables (Lin, 1990). *M. separata* has no diapause stage in its life history and the nocturnally-migrating moths engage in large-scale seasonal migration from south to north and back again in East Asia (Chen *et al.*, 1995; Lee and Uhm, 1995; Feng *et al.*, 2008). It can propagate all the year round in areas south of the 0℃ isothermal curve in January in China. In March – April, carried by southwesterly winds, the moths migrate to areas of Shandong, Henan and Shanxi provinces in the Yellow River and Huaihe River basins, where their progenies mainly cause damage to wheat. In May – June, the 2nd-generation moths migrate further northward from the above areas to Northeast China (*i. e.*, Liaoning, Jilin and Heilongjiang provinces), where damage is mainly to corn (Lin, 1990; Chen *et al.*, 1995). In a classic paper, Li Guang-Bo and collaborators (Li *et al.*, 1964) identified the migration route of *M. separata*

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in eastern China by large-scale mark-recapture studies and surveys. Many researches had also been done on the migratory physiology and biochemistry of this species, and the behaviour of moths (Cao *et al.*, 1995; Lai *et al.*, 2000; Yin *et al.*, 2003). Studies of atmospheric transport of the moths have been done with meteorological data, such as low-altitude wind fields, in combination with analysis of catches in pest-forecasting light traps situated at plant protection stations all over China. These studies have concluded that seasonal long-distance northward migration and southward return movements of *M. separata* are closely related to seasonal changes in the atmospheric circulation at the 850 hPa pressure level (approximately 1 500 m above mean sea level) (Zhao, 1982; Zhao *et al.*, 1985).

With the development of radar technology (Riley, 1989; Cheng *et al.*, 2002, 2005; Drake, 2002; Chapman *et al.*, 2003), Chen Rui-Lu and co-workers based at the Jilin Academy of Agricultural Sciences carried out field studies of the migration of *M. separata* in spring at Gongzhuling, Jilin province using a scanning radar, captive balloon and ground light trap (Chen *et al.*, 1989). Riley *et al.* (1995) caught specimens of *M. separata* at 155 – 220 m above ground level during autumn migration over southern Jiangsu province, and made observations of the common orientation of airborne migratory fauna. Feng *et al.* (2008) performed long-term monitoring studies on the autumn migration of *M. separata* at Beihuangcheng Island in the Bohai Sea between Northeast China and Shandong province in eastern China. Together these investigations have led to a better understanding of the take-off and vertical distribution in the air of *M. separata*, as well as of its displacement direction, speed, and orientation, during its spring and autumn migrations.

However, there has been no report on whole-season monitoring of this species, largely because of the cost of manning a scanning entomological radar for long periods and because processing of data from these units is time-consuming. The present study has identified the seasonal migratory parameters of *M. separata* in Northeast China using the automated vertical-looking radar (VLR).

2 MATERIALS AND METHODS

2.1 Site selection

In 2005, from the end of May to the end of September, a VLR, a searchlight trap and a ground-level light trap were set up in Zhenlai County (45°51′N, 123°12′E), Jilin province. Zhenlai is located at the meeting point of Jilin and Heilongjiang provinces, and Inner Mongolia autonomous region, where is within the main flight corridors for *M. separata* spring migration into Northeast China (Li *et al.*, 1964). Majority of this county is plain, with an average altitude of 150 m and a temperate-continental monsoon climate. The main crops there include corn and beans.

2.2 Radar observation

The VLR was constructed in cooperation with Jinjiang Electronic System Co., Ltd. (Chengdu, Sichuan province) in 2004 (Zhang *et al.*, 2007). It transmits at a frequency of 9.41 GHz (wavelength 3.2 cm), has a peak power of 10 kW, and directs its narrow linear polarized beam vertically using a 1.5 m-diameter parabolic-reflector antenna. The signal acquisition system uses a real-time program running on a dedicated computer to automatically monitor the insects passing directly overhead; the echo signals are displayed on a computer monitor and stored in real time as digital files for analysis. When the zenith-pointing beam of VLR is rotated for a circle, all data from the same height will be returned in 64 divided units in which angular resolution is about 5.63°. The radial space resolution of our VLR is 50 m, *viz.*, only one echo can be returned when there is more than one target in the 50 m range space for a certain azimuth scope. In our experiments, returning signals from the same direction were automatically and continuously stored in terms of height sections of 50 m without intervals. Each returned signal can provide four parameters including insect flying height, echo intensity, azimuth and time when the moths passed through the radar beam. According to the design, the detected targets are considered to be migrating insects, only when echo intensity is greater than 30 dB. In our field observation, the minimum intensity value is set to be 32 dB for migratory insect targets in the real radar program, so that only the echoes greater than 32 dB could be stored in the computer. For further analysis, amounts of each section could be retrieved from the stored data and written into a txt file every 5 min. In the txt files, effective height ranges from 250 m above ground to maximum detection range, with range-gate of 50 m, and filename is generated from the time of computer.

The VLR was set up in a flat open place where its beam was not subject to blocking or spurious reflections from nearby buildings. The radar was operated between sunset and sunrise each night (except on nights when it rained). In order to distinguish *M. separata* from other insects with

wind trajectory simulation. From the radar observation, the take off time of most moths of *M. separata* started at sunset and end at dawn, so the emigration routes were estimated by forward-tracking from the time of sunset, and the immigration routes by backward-tracking from a start time of dawn, time duration was 8 h. The minimum and maximum heights used for trajectory calculations were from 200 m to 2 000 m, which was determined from the radar observation. The software automatically stopped the analysis at the point where heights fell outside these limits. Daylight periods were excluded from the trajectory construction, as *M. separata* is a nocturnal migrant from the radar observation. Dates for radar observations and trap catches reported in this article denote the evening of that date through to sunrise of the next, and time is all given in Beijing time (UTC +8 h).

3 RESULTS

3.1 Seasonal dynamics of *M. separata* as revealed by light trapping

Evidence from the light traps revealed three key peak periods for *M. separata* moths during the 2005 season, the first from May 29 to June 2 (peak date June 1), the second from July 13 to 20 (peak dates July 15 and 19) and the third on September 11 (Fig. 3: A), there were a few *M. separata* moths captured at other time. On May 29, the number of *M. separata* moths caught in the searchlight trap suddenly increased. On June 1, when there was light rain (which did not interfere with the radar and trapping operations) in the vicinity, the number of *M. separata* moths in the searchlight trap added up to 2018, comprising 81.63% of all caught macro-insects (Table 1). On June 3, the number of *M. separata* in the searchlight trap declined markedly to 11, but this was the peak night for catches in the PS-15 light trap (Fig. 3: B). Catches of this species in both light traps were insignificant after June 10. In mid-July there were frequent thunderstorms locally, and the radar observations suffered some interference from the convective weather. On July 13, the site had medium to heavy rain, and the searchlight trap was switched off at 21:35 due to thunderstorms; nevertheless, 47 *M. separata* moths, accounting for 97.92% of the total macro-insect catch (Table 1), were found in the trap on the following morning (Fig. 3: C). There were further peaks in the searchlight-trap catches on July 15 and 19 with numbers reaching 700 per night. The peak period detected by the PS-15 trap was essentially the same as that for the searchlight trap. Catches of *M. separata* then gradually decreased and fell to zero after July 21. In the first ten days of September, several *M. separata* moths were caught in the searchlight trap and few in the PS-15. On September 11, the number in the searchlight trap suddenly increased to 124. On September 12, the number of *M. separata* decreased to 11 and fell to zero after September 14. It was noted that in all three migration periods the peak catches occurred either just before or during rainfall, Radar observation also recorded these three migration events.

Table 1 Proportions of all total macro-insects in the catch of searchlight trap

Date	Species	Number	Percentage
1st June	*Mythimna separata*	2 018	81.63
	Loxostege sticticalis	389	15.74
	Scotogramma trifolii	35	1.42
	Gryllotalpa orientalis	30	1.21
15th July	*M. separata*	743	61.40
	L. sticticalis	12	0.99
	S. trifolii	217	17.93
	Heliothis viriplaca	206	17.02
	Pyrausta nubilalis	32	2.64
11th September	*M. separata*	124	58.22
	S. trifolii	52	24.41
	H. viriplaca	37	17.37

Ovarian development of searchlight captures confirmed these migration characteristics of the *M. separata* moths caught from May 29 to June 2, 90% female moths had developed to grade Ⅱ – Ⅳ and there were no individuals of grade Ⅰ. The female-male ratio was greater than 1 (Fig. 3: D); peak catches in the searchlight trap occurred 1 d before those for the conventional PS-15 trap. Therefore, this peak period of *M. separata* catches is indicative of a typical long-distance immigration event.

Mid- to late July at the radar station corresponded to the eclosion period of the 1st-generation of locally bred *M. separata*. As shown by the searchlight and the PS-15 trap catches, *M. separata* moths were present over a more extended period and there was no lag between peaks in the two types of trap; similarly, ovarian development was concentrated at the stages of grade Ⅱ and Ⅲ (Fig. 4). These are typical characters of a mix of local and migratory populations. In September, temperatures in Northeast China rapidly decrease and crops become ready to harvest, so there would have been no food for larva to survive on. Most females caught in the searchlight trap on September 11 were of grade Ⅰ and Ⅱ. These observations could be

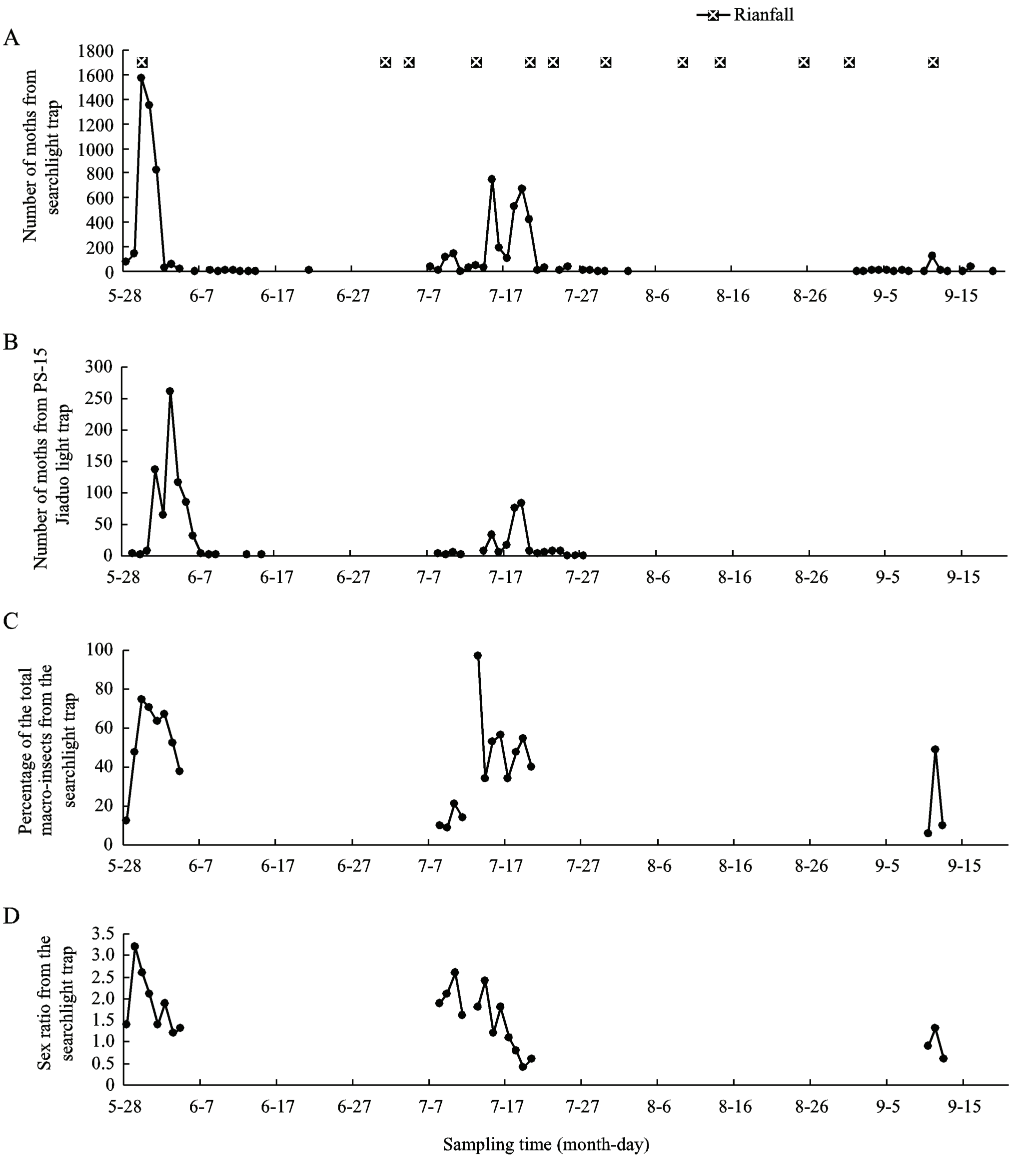

Fig. 3 Number of daily catches of *Mythimna separata* moths from the searchlight (A) and PS-15 light (B) traps, and the proportion of this species among all macro-insects in the catch in the searchlight trap (C), and the sex ratio (female/male) for the searchlight-trap catch (D) in 2005 at Zhenlai

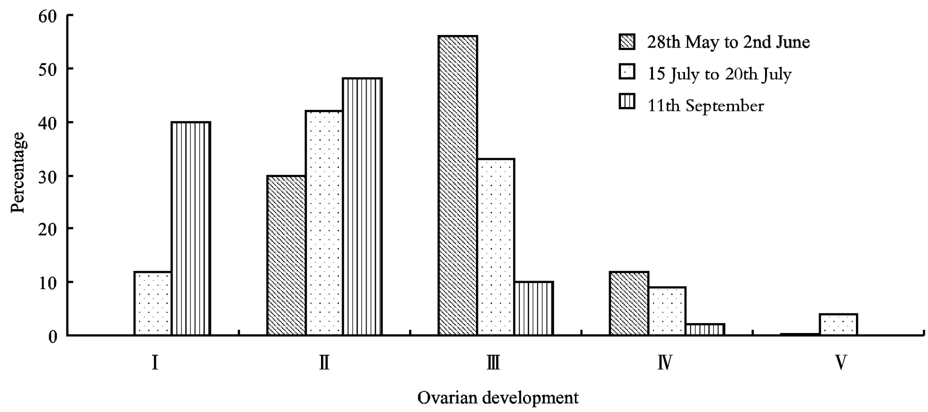

Fig. 4 Ovarian development status of female moths captured by the searchlight trap at Zhenlai during the peak migration periods of *Mythimna separata* in 2005

explained by migration of the 3rd-generation *M. separata* moths produced in the Hulun Buir region of Inner Mongolia.

3.2 Flight parameters of *M. separata* during the three migration events

Information on the variation of *M. separata* moth numbers with height and time through the night was extracted from the radar observations for the three migration events identified above; few echoes with typical characters of *M. separata* were detected by the VLR outside during these periods. Radar echoes increased simultaneously with light-trap catches during the three events, and especially on June 1, July 15 and September 11. Virtually all echoes disappeared after daybreak, supporting the view that these targets were mainly night-flying moths.

About 1 h after sundown (about 20:00) on June 1, radar echo numbers began to increase at 600 m height (Fig. 6: A). As the numbers increased further, the altitude range widened to 300 – 600 m. A peak was observed around midnight, when the echo number was more than 600. Target numbers then decreased, but slightly increased at around 03:00, last for 2 h before the final disappearance of targets after daybreak. Based on the timing and initial height of echoes recorded by the radar it was clear that *M. separata* moths were engaged in long-distance migration over the research site and that the migration duration was more than 8 h (Fig. 5: A).

The variation of the aerial density of *M. separata* with time during the summer migration was similar. For example, on July 15, about half an hour after sundown (about 20:00), radar echoes began to increase and they first appeared at heights of 300 – 600 m. The height of flight gradually increased along with the increase in echo numbers. A peak was observed at 21:00 , lasting about 1 h, and then the number of echoes decreased before another peak was observed starting at 23:00. Echo number at 600 m reached 800 m during this period. After about 03:00, echoes at other heights gradually disappeared, but some flight continued at 500 – 600 m, and flight duration was more than 8 h on this night (Fig. 5: B).

On September 11, take off events began at 19:00, the radar echoes were concentrated mainly at heights of 300 – 500 m earlier in the night, but very largely at 500 – 600 m after about 23:00, and flight duration was nearly 9 h on this night (Fig. 5: C).

3.3 Weather systems and migratory processes in *M. separata*

The migratory behavior of the *M. separata* moths was significantly influenced by meteorological conditions, especially the large-scale atmospheric circulation. It appears that the migtory moths actively took advantages of fast-moving low level jets in the high sky. The above findings showed that in spring, *M. separata* mainly migrated from the southwest, with the transmission of the fast and favorable predominant wind during that season (Fig. 6: A) make long-distance movements possible. In summer, when locally bred moths dispersed and migrated at the same time, the radar showed complicated density profiles, sometimes with two or more obvious layers at heights up to 1 000 m (Fig. 6: B). In autumn, the moths again flew at the height where the wind, which now had a large southward component, was strongest (Fig. 6: C): a behavior that appears adaptive given the lack of food locally at this season.

In late May, southwesterly winds prevailed over northern and Northeast China due to the influence of the Pacific subtropical high-pressure region. On June 1, a cyclone which formed in the upper air over the Sino-Mongolian border gradually moved southeastwards during the night. The center of the cyclone was located over the Tongliao region of Inner Mongolia at 18:00, and its influence extended across the whole of Northeast China, causing low to moderate rainfall all over the area. This provided favorable meteorological conditions for the long-distance migration of *M. separata*, and later its cessation as shown by the large number (2 018) of moths in the searchlight trap on June 1. A 24 h (a three-night backward trajectory because of daylight periods were excluded from the trajectory construction) backward trajectory analysis showed that population sources of *M. separata* recorded at the radar station on May 28, 29 and June 1 originated mainly from the Weifang and Linyi areas of Shandong province (Fig. 7: A). These putative sources are supported by National Agro-Tech Extension and Service Center (NATESC) reports of peak populations of *M. separata* moths in late May in the Heze, Linyi, Jining and Weifang areas of Shandong (http://cb.natesc.gov.cn/sites/cb/). On the evening of May 29, *M. separata* taking off from these areas of Shandong province and migrating across the Bohai Sea on the southwesterly winds then blowing would have reached Jinzhou, Panjin, and neighbouring regions in Liaoning province by the early morning of May 30. *M. separata* continuing to migrate on the evening of May 30 would have reached the Siping region of Jilin province on the early morning of May 31. *M. separata* emigrating from

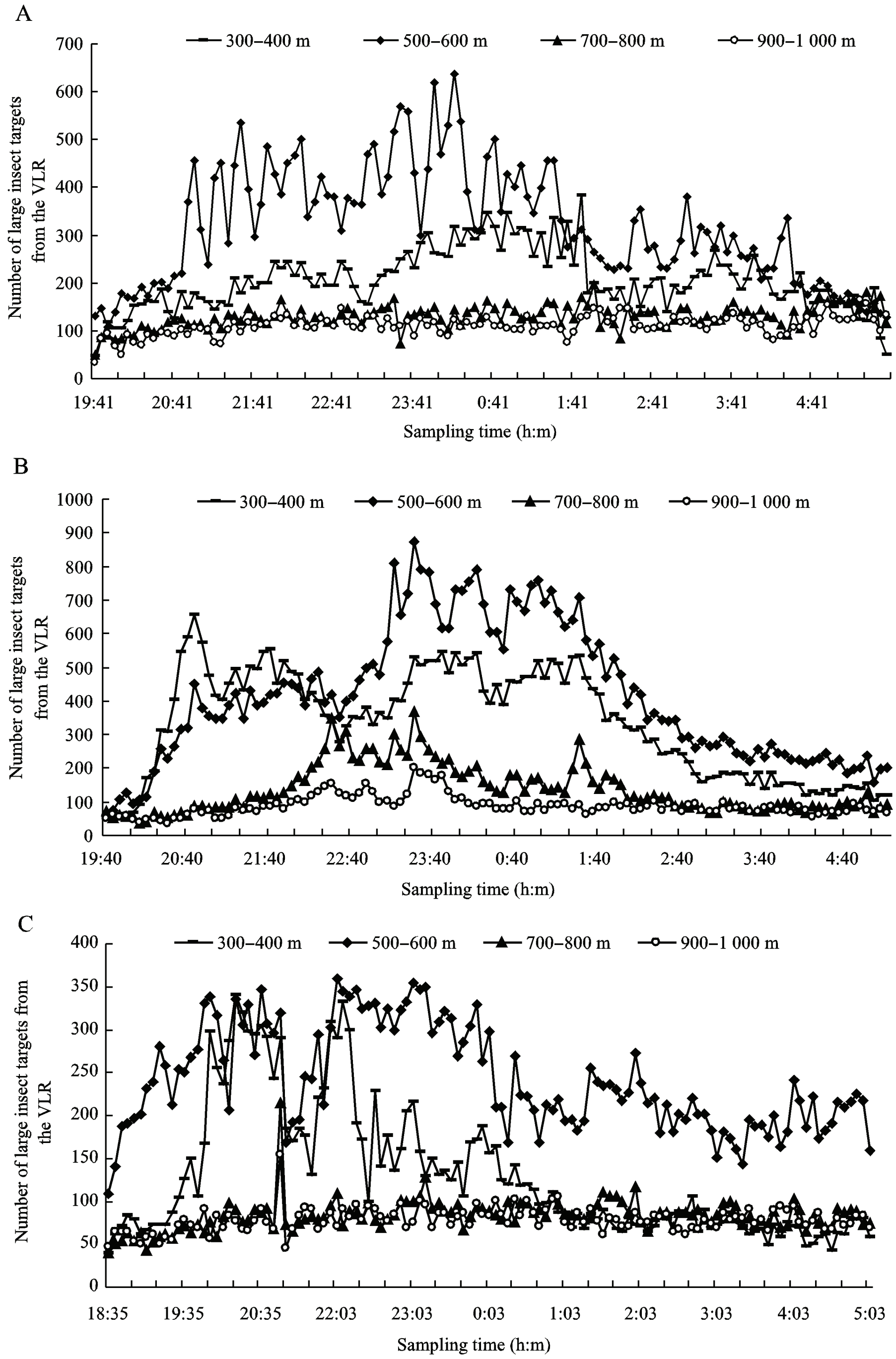

Fig. 5 Variation in number of large insect targets detected with the vertical-looking radar (VLR) at Zhenlai in 2005
A: June 1, sunset at 19:20, sunrise at 04:06; B: July 15, sunset at 19:37, sunrise at 04:10; C: September 11, sunset at 18:05, sunrise at 05:16.

Jilin province on May 31 would probably have fallen out and landed due to the influence of the cyclonic weather, producing the high catch numbers recorded at the radar station on June 1. A 12 h forward trajectory analysis showed that if some of these *M. separata* moths flew again on the evening of June 2, they could have traveled southeast into the central region of Jilin province (Fig. 7: A). Our trajectory analyses showed that the population sources of *M. separata* arriving in Jilin province at the beginning of June probably came from as far south as central and southern Shandong province, and that this requires a journey over several nights.

In mid-July, wind fields in the upper air of Northeast China were changeable, and convective weather was frequent. On July 15 and 19 - 20, there were many days of thunderstorms weather in Northeast China. Trajectory analysis indicates that *M. separata* observed on July 15 and 19 - 20, which were mainly the locally-produced 2nd-generation, were then subject to mass fallout over the area of Tongliao in eastern Inner Mongolia and Qiqihaer in northwestern

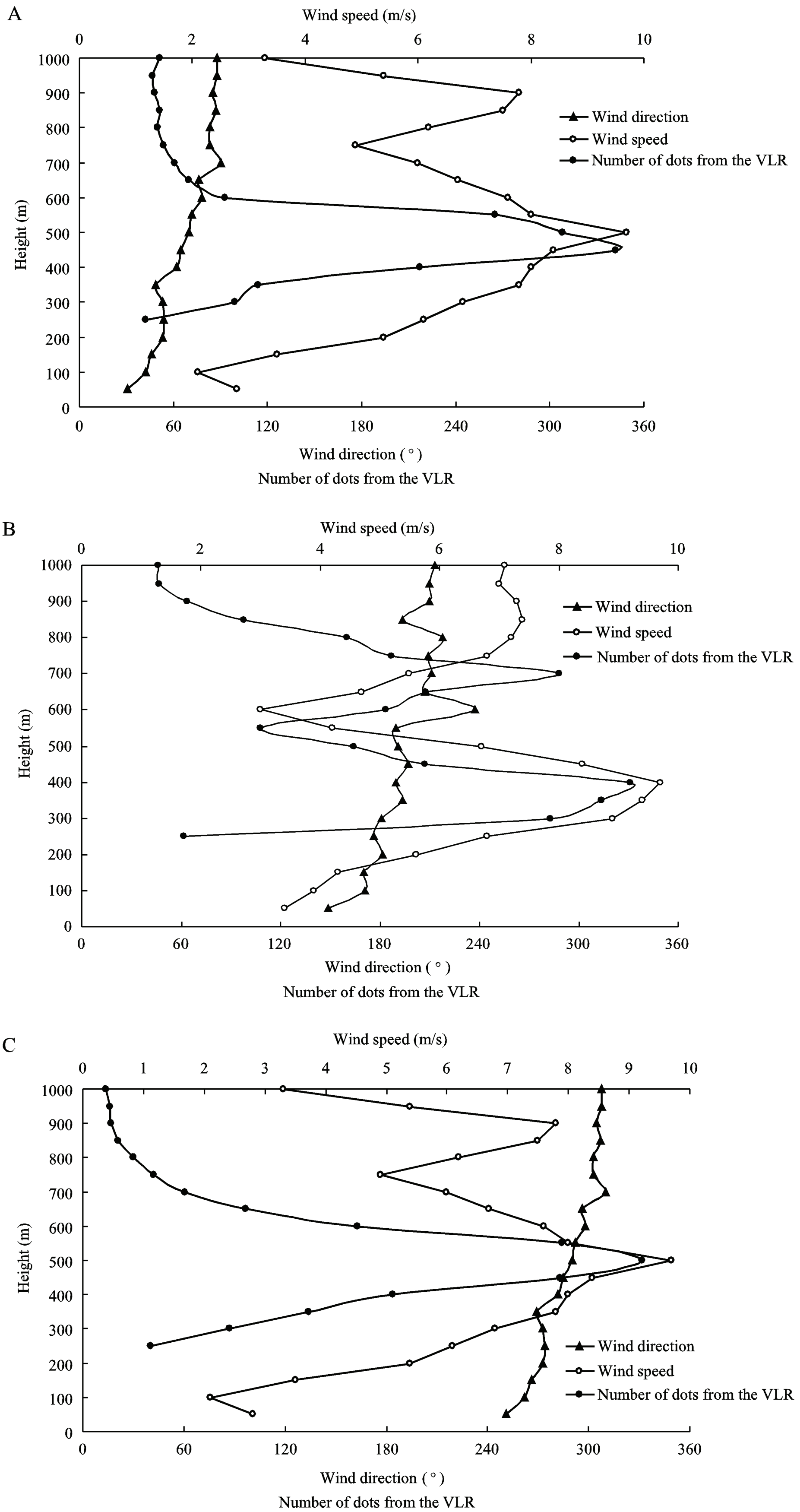

Fig. 6 Number of dots from the VLR, wind speed, and wind direction with height at Zhenlai on the nights of June 1 at 22:00 (A), July 20 at 00:00 (B), September 11 at 22:00 (C) at Zhenlai

4 DISCUSSION

There have been several attempts to determine aerial flight parameters of *M. separata* by various methodologies. Based on tethered flight in the laboratory, wind tunnel tests, and speculation about the relation between migration and temperature/humidity (Zhang and Li, 1985; Jiang *et al.*, 2003), and assuming an average ground temperature in June – August in Northeast China of about 20℃ (Beijing Meteorological Observatory Data Center, 1983), the migratory altitude would be expected to be about 300 m. By analyzing the relation between migration of *M. separata* moths and wind fields, Lin *et al.* (1963, 1964) concluded that *M. separata* moths in Northeast China migrate at about the altitude of the 900 or 950 hPa pressure level (*i. e.*, at ~ 400 – 900 m). Radar observations of the species' migratory activity at Gongzhuling, Jilin province in spring 1986 found that most migrated at altitudes below 400 m although there was some migration between 400 and 1 200 m (Chen *et al.*, 1989; Chen *et al.*, 1995). In the present study, through season-long radar observation and meteorological analysis, we found that the moths fly at obviously different altitudes depending on season and time of night, that the long-distance migration is wind-assisted, and that part of the individuals are able to continue in flight throughout the night. *M. separata* moth has different flight altitudes in different seasons: mainly 300 – 600 m in spring, higher in summer (when stratification was often present), and below 500 m in autumn. These findings all have potential value for predicting, forecasting and providing early warnings for this insect pest.

Downwind migration and orientation with respect to the wind have been shown in previous radar investigations of *M. separata* (Chen *et al.*, 1989; Riley *et al.*, 1995; Feng *et al.*, 2008). Simulation experiment by using flight mill indicated that temperature of the *M. separata* flight was 11 – 32℃, the optimum temperature is 17℃, and the lower was about 8℃ (Zhang and Li, 1985), therefore, the temperature is not a limiting factor in spring and autumn. Here we present evidence that in spring and autumn the moths select the altitude with the strongest wind speed and a favorable wind direction, thereby making possible the adaptive very long-distance migration of this species. Preferential migration at the altitude of the fastest winds, a behavior that enables movements of several hundred kilometers on one night, has also been found in migratory noctuids in other parts of the world (Chapman *et al.*, 2008, 2010). Movements of *M. separata* into Northeast China in late May and early June are greatly facilitated by the prevailing southwesterly winds, as shown by Chen *et al.* (1989) and the present study, with movements of several hundred kilometers being achieved.

The extent of a return migration of *M. separata* from Northeast China remains in question. After comprehensive analysis of topography and of monsoon and other weather systems, Zhai and Wu (2002) argued that *M. separata* movements into Northeast China in spring might represent a 'Pied Piper' effect because return migration southward in July – August would not be easy. Some radar studies have indicated that some return movement takes place (Feng *et al.*, 2008) but autumn movements of *M. separata* can also be in apparently disadvantageous directions (Riley *et al.*, 1995). In this study, it was found that movement in mid-July was influenced by frontal weather and variable wind fields leading to dispersal over a wide area of northern China, but not to an unambiguous southward displacement. An example of late migration (in September) was to the southeast – again not particularly conducive to a return to potential overwintering areas in southern China. There was only one night with significant movement in the autumn, and this involved only low numbers. The implication is that breeding by the summer generation at this latitude is not particularly successful. Trajectory analyses showed that *M. separata* migration is strongly influenced by weather factors, such as cold and warm fronts, cyclonic circulations, and rainfall. A more general conclusion is that regional air currents in a favorable direction during the main migration periods are an essential requirement for the adaptive long-distance migration of this species.

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东北地区粘虫的季节性迁飞行为

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摘要: 粘虫 *Mythimna separata* 是我国农业生产上的重要害虫, 为了明确其季节性迁飞行为参数, 本研究采用垂直监测昆虫雷达(vertical-looking radar, VLR)及相关辅助设备的长期自动观测, 结合基于 GIS 的大区环流和轨迹模拟, 调查分析了 2005 年东北地区粘虫季节性迁飞行为。结果表明: 粘虫在不同季节和夜间不同时间空中飞行高度具有明显差异, 空中飞行行为受气象条件尤其是空中风场影响较大; 春季和秋季主要借助气流运载进行大规模长距离迁飞, 夜间持续飞行时间可达 9 h, 多数个体能完成整夜飞行, 春季迁飞高度主要在 300 ~ 600 m, 秋季飞行高度相对较低主要在 300 m 以下和 400 ~ 500 m。夏季雷达回波有明显的成层现象, 最高可达 1 000 m, 主要集中在 500 m 和 700 m 两个高度层。轨迹分析显示: 5 月 29 日由山东潍坊、临沂等虫源地起飞的黏虫, 顺西南气流越海迁飞, 6 月 1 日在气旋天气影响下, 在吉林省白城等地降落; 7 月中旬主要为当地黏虫受对流天气影响进行短距离迁飞扩散; 9 月 11 日虫源来自内蒙古呼伦贝尔, 顺西北气流向吉林省东南方向迁飞。研究结果为东北地区粘虫的有效防控提供了技术支撑。

关键词: 粘虫; 迁飞; 雷达监测; 轨迹分析; 垂直监测昆虫雷达; 灯诱; 虫源

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